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The purpose of this AFOSR DURIP grant was to acquire a new amplified femtosecond laser system for micromachining of precision features in thermal spray coatings. Such devices are particularly useful for fabricating sensors for very harsh environments. The combination of versatile material addition through direct-write and the precision, high-quality micromachining from an ultrafast laser represents an enabling capability for DoD programs, applications, and future directions.

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FINAL REPORT

DURIP: Next-Generation Ultrafast Laser for Micromachining of Sensors, Electronics, Materials Synthesis and Analysis

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Co-PIs: Profs. *Sanjay Sampath*, *Andrew Gouldstone*, and *Clive Clayton*, Materials Science
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Introduction

The purpose of this AFOSR DURIP grant was to acquire a new amplified femtosecond laser system for micromachining of precision features in thermal spray coatings. Such devices are particularly useful for fabricating sensors for very harsh environments. The combination of versatile material addition through direct-write and the precision, high-quality micromachining from an ultrafast laser represents an enabling capability for DoD programs, applications, and future directions.

The laser system is a state-of-the art design, with *reliability* and *ease of use* being two driving factors in deciding which system to purchase with this DURIP funding. The selected laser system has been purchased and installed and is very nearly a turn-key system, as it is controlled by two laptop PCs that make turning the system on and off both easy and repeatable. Very minimal tuning and adjustment are needed, which is a far cry from the previous laser the PI was using, which required constant realignment and rarely produced a decent beam quality.

The complete laser system consists of the following key components:

1. A *femtosecond seed oscillator* to produce low energy femtosecond laser pulses
2. A *laser pump* for the femtosecond oscillator (#1)
3. An *amplifier* that increases the energy of the femtosecond seed oscillator
4. A *laser pump* for the amplifier

These components work in tandem to produce amplified ultrashort laser pulses that can be used for precision material removal and patterning of features with feature sizes down to 10 μm or less. Additional support items such as lenses, motion control, power attenuation, etc. round out the complete system.

The key components in the system are shown in the figure below.

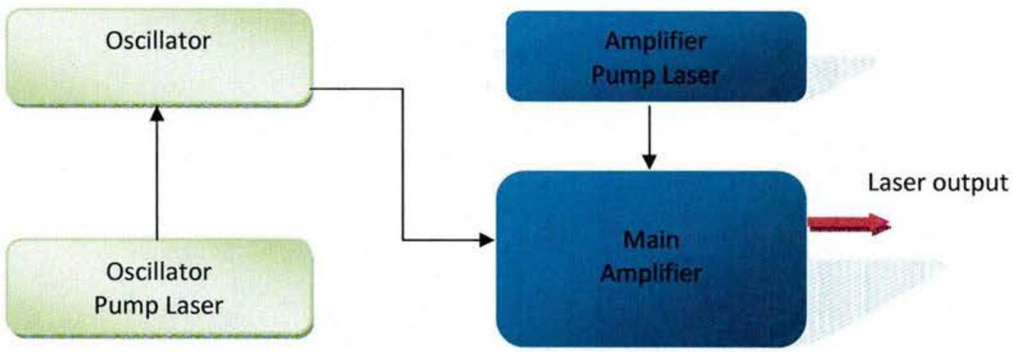

Figure 1: Schematic of key components of laser system involved in producing high energy ultrafast laser pulses. The equipment acquired with the DURIP funds includes the main amplifier and amplified pulse laser (blue items above). The oscillator/oscillator pump laser (green) were already available and from the PI's previous ultrafast laser system, and were integrated into the final system.

Review of Commercially Available Systems and Reasons for Final Choice

Three potential vendors were considered for the laser purchase: (1) *Coherent, Inc.* (CA), (2) *Spectra-Physics Corporation*, and (3) *Clark-MXR (MI)*. A fourth vender of such systems, *Quantronix, Inc.* (NY), was not considered because the company is up for sale and the future of their products and services is unclear. For the venders considered, each had advantages and disadvantages, and each laser system was thoroughly investigated before the final purchase decision was made.

Coherent was considered initially because they offer a so-called "one box" solution, in which all four of the devices in Figure 1 above fit into a single temperature-controlled platform that also has a relatively small footprint on the optical table (thus saving space). This option was rejected however, because the system requires a single software program to control all lasers, but because the oscillator is provided by *Spectra-Physics* and the amplifier by *Coherent*, there were concerns that the system would not work smoothly together. Also of concern was serviceability: either vender could lay the blame at the other's feet if there were problems. The PI visited Coherent (no DURIP funds were used for the trip) and personally inspected the proposed system, however the build quality, layout, and ease of service were all less than ideal.

We similarly looked at the *Clark-MXR* device, which is also a one-box solution, however Clark-MXR is a small company that has only a single service representative for the entire U.S. territory. They also use a unique proprietary laser design that is likely to be not well understood by other service technicians in the field. Despite the fact that the system was attractive from a cost point of view, there were serious concerns about long-term service and reliability with this unit, and it was also thus rejected from consideration.

We finally decided to purchase the *Spitfire Pro* system from Spectra-Physics. Since our oscillator was from Spectra-Physics, we were comfortable that both the old and new systems would work together. Furthermore system service can be done by a single point of contact for the entire system, which is a significant advantage. Finally, the PI has used Spectra-Physics lasers for over ten years and has had excellent service and support for their products. Spectra-Physics also included a three-year full service contract for the laser, including the pre-existing laser components. For all of these reasons, the laser was purchased from Spectra-Physics. The PI also visited the Spectra-Physics facility in California to inspect the proposed system (no DURIP funds were used for the trip). The PI was impressed with the quality of the build, the knowledge of the employees, and the attention to detail that was evident in this system.

System Installation

The Spectra-Physics system was ordered in June, 2006 and installed in October, 2006 in the laboratory facilities of the P.I. (Jon Longtin). The room was modified to include additional thermal control by adding a stand-alone heat pump and air conditioning unit to provide additional temperature stability for the new system.

The system can provide pulses of up to 2.1 mJ at a pulse duration of about 100 fs, a wavelength of 800 nm and a pulse repetition rate of up to 1000 Hz. The laser beam is directed through a lens and attenuating system to focus and attenuate the beam as needed, after which it is directed to a three-axis precision motion control system (previously owned) used to move the workpiece being laser processed. The motion is controlled by a personal computer, which can be programmed to both move the workpiece and also turn the laser on and off as needed.

The system has been running well since its installation, particularly after thermally stabilizing the room in which the laser resides. It is routine, in fact, to turn the laser on and have it be warmed up, stable and ready for use in 30 minutes or less with no adjustments needed. Minor tuning is required only once every few months, and the reliability of the system has been very good to date. There has been one major service call on the system to replace a Pockel's cell and controller in the Empower pump laser. This work was done by the service technician in house and was performed at no cost due to the service contract we have on the system.

Pictures of the system and additional details are provided below.

Figure 2: Overview of installed system showing all three laser systems: *Mai Tai* oscillator (front, left), Empower pump laser (front, right), and *Spitfire Pro* amplifier system (rear, right). Positioning system and lenses are at far end of table. The empty area of the table is available for experiments and setup. The entire table has active air suspension to minimize vibration and noise.

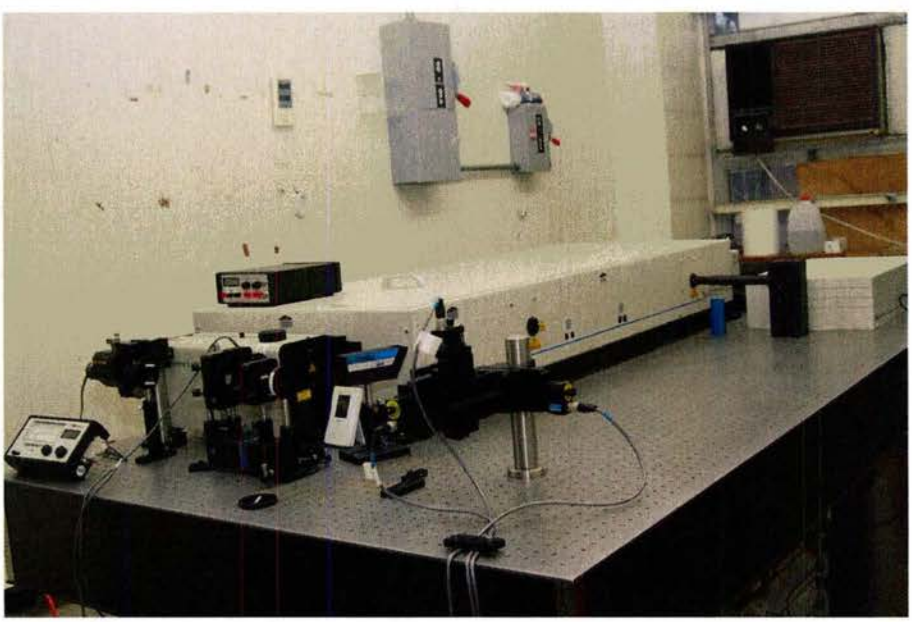

Figure 3: Front view of same system shown in previous figure. The small tan box just behind the optics and just in front of the amplifier system is a *Positive Light* single-shot autocorrelator, which is used to measure the pulse duration of the laser using a time-of-flight pulse splitting technique.

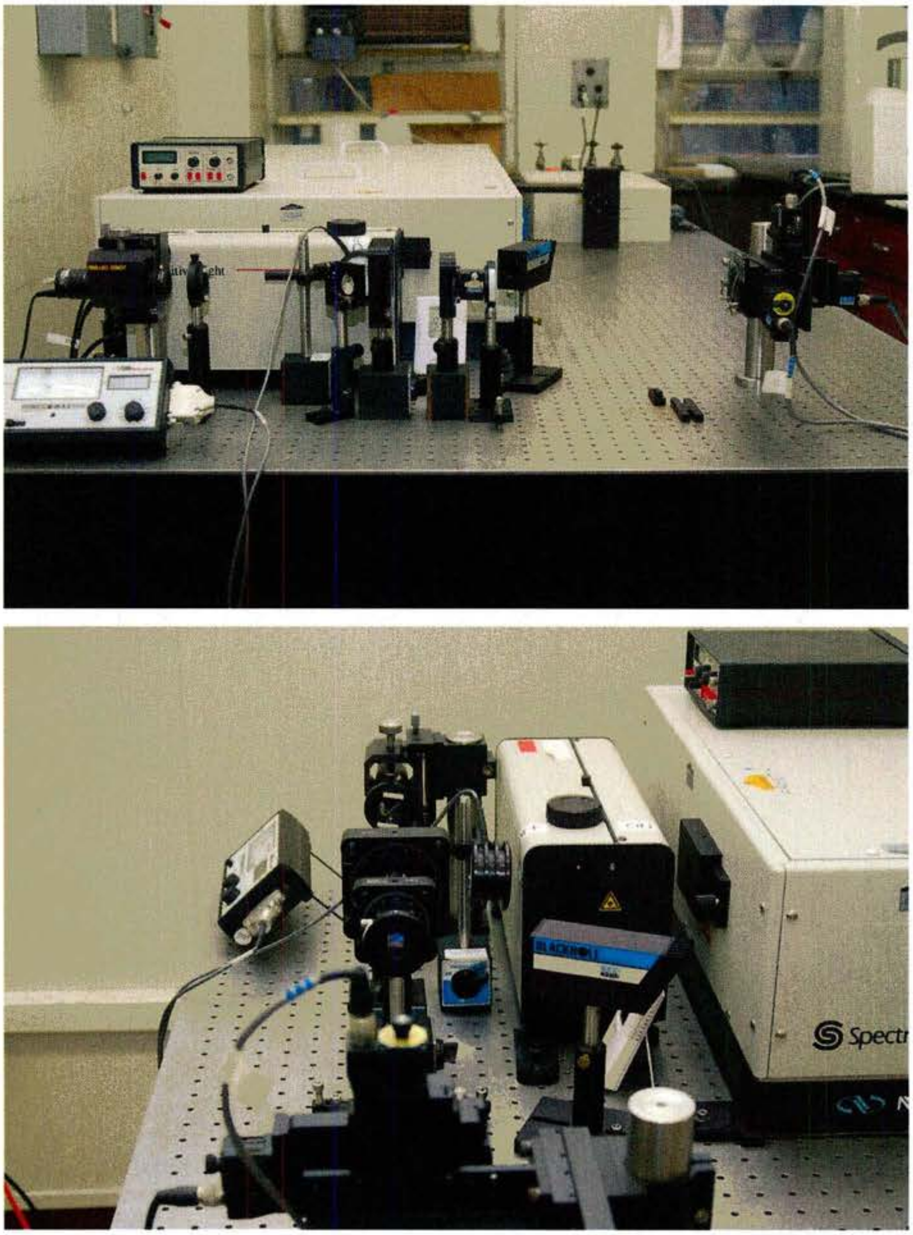

Figure 4: Front view (top figure) and side view (bottom figure) of the optical components. The beam exits the laser on the right side of the amplifier and passes through the autocorrelator. It is then redirected to the left with a single turning mirror and sent to a polarizer-beam splitter pair to attenuate the beam energy. The blue and black device is a beam stop to absorb the deflected laser beam from the attenuating system. The motion system is shown in the far right of the top figure and consists of three mutually perpendicular motion stages that are controlled by a single computer interface.

Figure 5: Two computers used to control laser. The left computer runs (only) the software for the *Mai Tai* oscillator laser. The right computer controls both the *Empower* pump laser and *Spitfire* amplifier systems.

Education and Research Mission with the New Laser

The ultrafast laser described above will be used primarily to develop protocols and actual processing of materials used for sensors for very harsh environments. The material removal mechanism for ultrafast lasers is *non-thermal* in nature, and as a result can provide increased precision, feature size, reduced thermal damage, and material versatility to address emerging DoD needs. Ultrafast lasers have pulse durations of 100–200 femtoseconds (1 fs = 10–15 s), and provide substantially improved feature quality with negligible thermal damage, all while maintaining excellent throughput, when compared to traditional lasers having pulse durations of 1 nanosecond or longer. Ultrafast laser micromachining is a natural for processing direct-write coatings formed from thermal spray processes, a research area of considerable interest to the DoD and to us at Stony Brook. The material versatility of ultrafast lasers complements the versatility of the thermal spray direct-write process. Features thus far made by this method are extremely well-defined, and the performance of the resulting fabricated devices, e.g., strain gages and microheaters, is very promising. However, work to date was done largely on a prototype 'academic' ultrafast laser system that had many disadvantages. The opportunities for improvement in the laser micromachining capabilities of thick films and the resulting applications are significant with the newly acquired laser system.

Similarly, from an educational perspective, the laser provides a unique vehicle for student training in lasers, optics, micromachining, and laser-material interactions. Given the ever-increasing dependence

on optical systems for measurement, signal processing, communications and manufacturing, such experience is invaluable. This is especially true for lasers and optics, as there are very few formal training programs for these schools in the U.S.

The PI and Co-PI wish to again express their sincere thanks for the opportunity to acquire this laser system through the DURIP program.

— **Jon Longtin**, Principle Investigator (November 7, 2007)